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**Limits and Capabilities of Cooperative Diversity:
A Network and Protocol Perspective**

by

Oscar Bejarano

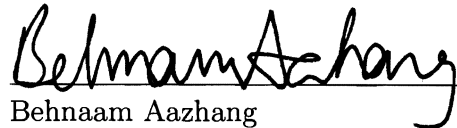
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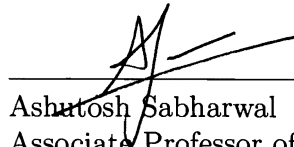
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ABSTRACT

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Physical-layer cooperation has been demonstrated to vastly improve wireless link reliability and end-to-end throughput by exploiting spatial diversity. Nevertheless, its performance in operational networking environments is uncertain. Cooperative link gains can be potentially diminished by factors such as i) increased transmission footprint due to the activity of the cooperative relay, ii) non-ideal node location due to the structure of a planned network, or iii) the inability of cooperation protocols to recognize the channel's global state, hence leading to increased congestion. In this work, we identify and evaluate these key factors affecting the performance of cooperative techniques in small- and large-scale topologies. Our evaluation reveals that throughput gains from cooperation achieved in atomic, isolated topologies, decrease significantly when implemented at network-scale scenarios. Furthermore, our study provides a deeper understanding of the regimes in which cooperation performs poorly, and can help in the design of effective protocol solutions for such cases.

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Chapter 1

Introduction

To mitigate losses in performance due to signal fading and multipath effects induced by the wireless channel, several studies have proposed the use of diversity [1–3]. The main idea behind diversity is to take advantage of the intrinsic nature of the wireless channel with the purpose of transmitting redundant signals over multiple antennas interacting with multiple relatively independent channel realizations between a source and a destination. At the receiver, the various copies of the same signal are received nearly simultaneously, each having different fading characteristics that ideally would allow perfect signal reconstruction. However, having multiple antennas can be impractical in many mobile wireless devices due to their small size precluding the antenna separation required to achieve maximal gains from diversity [3, 4].

Recently, *distributed* antennas (located at different nodes), have been shown to provide the same benefits that space diversity achieves without the need for single-device antenna arrays [2]. In order to achieve this diversity gain, several cooperation techniques have been introduced with the purpose of exploiting the ability of neighboring nodes not only to overhear other’s transmissions but also to serve as an additional antenna that can be used to attain such spatial diversity. Some of the major motivations for implementing cooperation are to diminish the dependence on the quality of a particular path of the wireless channel, and perhaps on the distance between a source-destination pair as well, by means of increasing link performance and transmission reliability.

There exists an extensive body of literature providing evidence that physical-layer cooperation can significantly improve the rate and reliability of wireless links [4–9]. Most prior work has considered different elements of cooperation such as capacity upper-bounds, outage behavior, and protocol development. However, no prior work has studied the criteria for which cooperation would positively or adversely affect throughput performance in a network setting.

This thesis presents an evaluation on the performance of cooperative protocols in common networking scenarios considering everything from fully connected topologies, to cases leading to information asymmetry in both isolated and network-wide designs. In particular we make the following two contributions. First, we perform a study of the elemental network factors affecting the gains that can be achieved through cooperative techniques under different small-scale networking scenarios consisting of at most two flows. We identify some of these key networking factors to be:

- Topological configuration especially when there is no knowledge about the overall network state beyond carrier sensing, as it is the case of hidden terminal scenarios.
- Source-destination separation distance due to the high dependency on the relay node to overhear transmissions from both the source and the destination in order to trigger cooperation, and the increase in magnitude of path loss effects.
- Relay position with respect to the assisted flow for the same reasons given in the previous bullet.
- Increased spatial footprint due to the activity of an additional transmitter, thus leading to an increase in interference especially in network-wide scenarios.

This evaluation has the goal of helping us understand under which regimes cooperation will, or will not work, and why. Furthermore, we pose the question of whether we should just use traditional techniques such as two-hop packet forwarding, or rate adaptation instead of cooperating for a specific transmission. We demonstrate that cooperation is able to achieve high throughput gains that outperform these other techniques when implemented in small-scale networking scenarios.

Second, we extend our evaluation from the one-flow and two-flow scenario to the study of larger scale networking configurations consisting of significantly more complex topologies such as ad hoc and mesh networks. Our evaluation of large-scale topologies reveals that current cooperation protocols are only capable of achieving modest gains, hence opening a wide variety of research questions regarding potential enhancements as to how we can achieve the same gains as with the atomic cases.

The rest of this thesis is structured as follows. Section 2 reviews the concept of physical layer cooperation and describes the experimental methodology we followed to perform our evaluations. This section also presents the literature review. Sections 3, 4, and 5, cover a variety of small-scale topologies where we determine how cooperation works in very isolated scenarios. In section 6 we analyze the effects on the overall performance of a network that is caused by the increased transmission footprint of the relay when cooperation is enabled. Further, section 7 deals with large-scale networks, and finally in section 8 we present our concluding remarks.

Chapter 2

Background and Literature Review

In this section we first present an overview of physical-layer cooperation and the experimental methodology we followed throughout this entire work. We also discuss the protocols used to evaluate cooperation as well as the key tools needed to implement such protocols. Furthermore, this section covers some of the most relevant prior work on cooperation and spatial diversity.

2.1 Background on Cooperation

Physical-Layer cooperation is a technique that mimics the basic working principles of MIMO/MISO communication systems, with the purpose of achieving similar performance. That is, it takes advantage of spatial diversity and the relatively independent channel realizations seen by each antenna in a particular device. However, in cooperation, this is done in a distributed manner by exploiting the presence of multiple single-antenna nodes, which by operating together can emulate an antenna array [10].

In figure 2.1 we present an example where cooperation is used. Both the source and the relay act as if they were a single multi-antenna device by transmitting cooperative packets to a common destination. Here, the relay takes the form of a neighboring node that is within carrier sense range from both the source and the destination. In order to have simultaneous transmissions from multiple sources to a common receiver without inducing a collision or destructively combining different signals, cooperation

employs some form of orthogonalization. This orthogonalization can be achieved in either the frequency, time, or spatial domains [3].

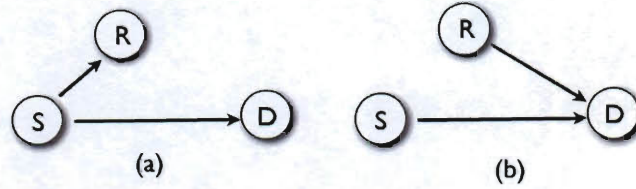


Figure 2.1 : Graphical representation of the concept of physical-layer cooperation. Source transmits data to its destination in a 1st time slot (a), and relay assists via a cooperative retransmission in a 2nd time slot (b)

There is an extensive body of literature on a wide variety of cooperative schemes, each following a different algorithm that dictates how and when this cooperation takes place. However, in general these schemes can be classified according to the technique and processing employed by the relay node [11]. The two most commonly used and known techniques are amplify-and-forward (AF) and decode-and-forward (DF). In AF, the relay simply applies some gain to the received signal and then forwards it. On the other hand, DF forces the relay to attempt to decode every transmission from the source and forward only those packets that were received without any errors.

Broadly speaking, both of these techniques can be employed in one of two ways by each cooperation protocol. *Reactive* cooperation protocols use explicit feedback from the destination to trigger cooperative transmissions at both the source and the relay; see for example [4]. These schemes rely on the use of different rates for the packet preamble and the payload. Usually, the preamble is sent at a much lower rate (i.e. base rate) in order to increase the probability of successful reception, while the payload is sent at a higher rate. A cooperative transmission is triggered by means of negative acknowledgements (NACKs) which are sent by the destination only in the

case that the preamble is decoded but not the payload. Such protocols are based on spatial diversity which translates into using antennas at different locations and implementing space-time block codes (STBC) in order to achieve signal orthogonalization. *Proactive* protocols, on the other hand usually rely on either frequency-, time- or no-orthogonalization at all, as shown in [12, 13].

In our work we focus on reactive (On-Demand) cooperation employing an AF technique and consider only orthogonalization in the spatial dimension by employing STBC, specifically, Alamouti codes [14]. That is, the protocols we implement and evaluate consist of feedback-based (NACK-based) protocols that exploit diversity by having multiple single antenna nodes cooperating with each other.

2.2 Cooperation Protocol Implementation

For our evaluation we implement both a real, existing cooperation protocol as well as an idealized, unrealistic scheme. The unrealistic protocol allows us to establish both a best-case as well as a worst-case scenario, and it is merely for comparison purposes. Best-case in the sense that even if the relay is not within carrier sense range from both the transmitting source and its destination, it will still cooperate whenever it is needed. On the other hand, worst-case since the transmit footprint of such flow is much larger, meaning that the induced interference is much higher as well. Both feedback-based cooperation protocols are implemented in simulation and in a physical testbed.

First, we implement a protocol that has a very close resemblance to the real protocol known in the literature as Distributed On-Demand Cooperation (DOC), which is described in detail in [4]. In a nutshell, DOC is a reactive protocol that uses NACKs to trigger cooperation but only whenever the destination determines that the

failed reception is due to a channel fade and not due to a collision. This distinction is done with the purpose of not adding any extra congestion to the network. However, the implementation we use differs from DOC in that NACKs are always sent regardless of the cause of the failure. We discuss the reason for using this scheme at the end of this subsection.

Then, we implement an unrealistic “benchmarking protocol” which we denote as *Ideal Cooperator*. This scheme is also feedback-based and on-demand. However, in this protocol we make sure that two events occur with 100% probability. First, the NACK that triggers a cooperative transmission is always successfully received by both the relay and the source. This guarantees that cooperation will always take place whenever it is needed. Second, all data packets from the source to the relay are successfully received so as to make sure the relay is always ready to cooperate.

We use the modified DOC protocol to evaluate small-scale topologies in both simulations in ns-2* as well as in the WARP[†] platform using the DOC implementation from [4] as a base. We use the modified version to understand the role of the NACK without much concern about congestion since we are dealing with at most two flows. However, as we move into bigger topologies we use both the benchmarking protocol as well as the actual DOC implementation since now we consider many more flows, hence congestion in the network becomes a major issue that we need to deal with.

2.3 Analysis of Small-Scale Scenarios

To evaluate cooperation, we first identify atomic scenarios consisting of only one or two flows. This evaluation allows us to identify the performance characteristics of

*Network Simulator - <http://www.isi.edu/nsnam/ns/>

[†]WARP - warp.rice.edu

cooperation as we vary key elements that influence the behavior of the relay such as transmit power or node positioning (topological factors).

When dealing with larger scale scenarios where node interaction becomes more complex and unpredictable, we observe a combination of all the different phenomena that are also encountered in a wide variety of atomic scenarios. Thus, the results obtained in such isolated experiments allow us to understand those results observed in more realistic and complex scenarios. These studies are performed via a combination of over-the-air experiments in WARP as well as controlled simulations in ns-2 (version 2.34). Refer to table 2.1 and 2.2 for a list of parameters used in our simulations and our physical experiments, respectively.

2.4 Analysis of Large-Scale Scenarios

We further extend our analysis to more complex topologies such as ad hoc and mesh networks consisting of multiple flows where nodes interaction becomes much more unpredictable due to channel characteristics and aleatory positioning of the nodes. Moreover, we emulate the existing wireless mesh network TFA[‡]. We use the same thresholds, antenna gains reported at each angle, and types of antennas (i.e. directional and omnidirectional). Due to the high number of nodes employed for these studies, we are restricted to performing only simulations instead of over-the-air experiments. Nevertheless, we make an effort to set the thresholds, propagation model, and parameters so that they resemble those of real-world operating networks as closely as possible.

[‡]Technology For All - tfa.rice.edu

Carrier Frequency	2.427 GHz
Transmit Power	10dBm
Header Rate	BPSK (1/2 rate code)
Payload Rate	64-QAM (3/4 rate code)
Packet Size	1412 Bytes
Traffic Pattern	Fully Backlogged Flows, CBR
Fading Model	Nakagami (moderate fading)
Maximum Retries	1

Table 2.1 : Simulation Parameters

Carrier Frequency	2.427 GHz
Transmit Power	10dBm
OFDM Symbol	64 Subcarriers
Header Rate	BPSK (6 Mbps)
Payload Rate	16-QAM (24Mbps)
Packet Size	1412 Bytes
Traffic Pattern	Fully Backlogged Flows, CBR
Maximum Retries	1

Table 2.2 : WARP Parameters - MAC and PHY Implementation

2.5 Experimental Platform

For our over-the-air experiments we utilize the Wireless Open-Access Research Platform (WARP) board developed at Rice University. The board is a fully programmable wireless platform consisting of three main components:

1. A Xilinx Virtex-II Pro FPGA.
2. Four daughter card slots for connecting up to four 2.4/5 GHz radio boards able to support wideband applications (e.g. OFDM).
3. 10/100 Ethernet port, and other support peripherals.

The current state of the platform's OFDM physical layer supports BPSK, QPSK, and 16-QAM modulations in 10 MHz. To control the boards, conduct experiments, and gather data in real-time, we use WARPnet[§], a framework that enables communication among wireless nodes in a network setting. WARPnet provides a software interface connecting the WARP boards and a host PC running server and client scripts, via an ethernet switch. In Fig. 2.2 we present our experimental setup.

2.6 Space-Time Block Codes

Transmitting two copies of the same signal simultaneously could potentially lead to a destructive combination of the waveforms at the destination as it is observed with multipath interference. Therefore, cooperation could actually degrade the performance of a system if this is not taken into account. To avoid this issue, we rely on the use of Alamouti space-time block codes (STBC) [14], which allow two different

[§]<http://warp.rice.edu/trac/wiki/WARPnet>

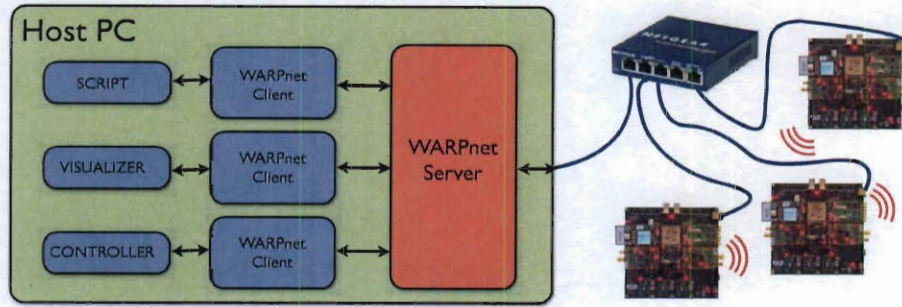


Figure 2.2 : WARPnet Configuration - A host PC runs both client and server scripts and communicates with the WARP boards to retrieve statistics and conduct experiments

transmitters to encode data into two waveforms that can be simultaneously transmitted and decoded at the destination. Such a transmit diversity scheme is able to provide the same diversity order as that of a maximal-ratio receiver combining (MRRC) implemented with two antennas at the receiver. Moreover, this scheme can achieve a diversity order of $2M$ by using two transmit antennas and M receiver antennas without requiring any bandwidth expansion, thus not having to sacrifice spectral efficiency [14].

In general, Alamouti STBC encoding works as follows [14]: During a given symbol period, two signals s_0 , and s_1 are simultaneously transmitted by antennas 0 and 1 respectively. Then, in the next symbol period, antenna 0 transmits $-s_1^*$ while antenna 1 transmits s_0^* , where $*$ represents the complex conjugate operation. The encoding and transmission sequence of data symbols is shown in Table 2.3. At the receiver end, the received waveform consisting of the weighted sum of transmitted signals (where the weights correspond to channel coefficients) [11] is translated into the original sequence of symbols as specified in [14].

In our experiments we use Alamouti STBC in a distributed manner by considering

	Antenna 0	Antenna 1
time t	s_0	s_1
time $t+T$	$-s_1^*$	s_0^*

Table 2.3 : Encoding sequence for Alamouti STBC

both the source and the relay as our two transmit antennas as explained in [4]: First, during the initial transmission, the source generates the waveform that will constitute Stream A. Then, if a retransmission is required, the source will re-encode the data as the waveform that will now constitute Stream B. The cooperative retransmission will then consist of the relay sending Stream A (which was obtained from the first transmission), and the source sending Stream B simultaneously.

2.7 Nakagami-m Propagation Model

In all simulations we utilize the Nakagami-m radio propagation model. Compared to other models such as Two-Ray Ground or Shadowing, Nakagami features more configurable parameters that allow for a more realistic representation of the wireless channel [21]. This model is able to model anything from a perfect free space channel to a very fast fading channel. We justify our topological arrangements based on an analytical evaluation of the propagation model used in the simulator, thus providing a quantitative analysis of the interactions between flows in the network. That is, based on the probability of packet reception for a given set of parameters, we choose the most suitable separation distance between nodes in a network to create the different topologies.

Killat et al. [18], derive the probability of packet reception as a function of distance

and intended communication range based on the Nakagami model: The probability density function of the Nakagami model is given by

$$f_d(x; m, \Omega) = \frac{m^m}{\Omega^m \Gamma(m)} x^{m-1} e^{-\left(\frac{mx}{\Omega}\right)} \quad (2.1)$$

where x is the received power for a given average power strength Ω at a distance d .

Consequently, the corresponding cumulative density is

$$F_d(x; m, \Omega) = \frac{m^m}{\Omega^m \Gamma(m)} \int_0^x z^{m-1} e^{-\left(\frac{mz}{\Omega}\right)} dz, \quad (2.2)$$

where m is the fading parameter and the gamma distribution is given by

$$g(x) = \frac{b^p}{\Gamma(p)} x^{p-1} e^{-bx} \quad (2.3)$$

Observe that by setting $b = \frac{m}{\Omega}$ and $p = m$, equation (2.1) resembles a gamma distribution. Furthermore, the probability of successfully receiving a packet is based on a receive threshold R_x :

$$Pr(x > R_x) = e^{-\left(\frac{mR_x}{\Omega}\right)} \sum_{i=1}^m \frac{\left(\left(\frac{m}{\Omega}\right)R_x\right)^{i-1}}{(i-1)!} \quad (2.4)$$

An intended communication range from the transmitter defines, on average, the distance at which Rx can be detected. In this case, a quadratic path loss that follows the Friis model yields

$$R_x = \frac{P_{tx}}{Q^2} G \quad (2.5)$$

where P_{tx} denotes the transmit power, Q denotes the intended communication range, and G is given by

$$G = \frac{G_t G_r \lambda^2}{(4\pi)^2 L} \quad (2.6)$$

G_t and G_r represent transmit and receive gains respectively, λ the wavelength, and L is the path loss factor. Finally, the average reception power $\Omega(d)$ is given by

$$\Omega(d) = \frac{P_{tx}}{d^2} G. \quad (2.7)$$

Based on this derivation, we can determine the probability of packet reception at a given flow based on the distance between the source node and the destination. To visualize this, in figure 2.3 we plot the probability of packet reception as a function of the distance between nodes, for different intended communication ranges. It is important to mention that such intended communication range is just another parameter that can be controlled in the simulator.

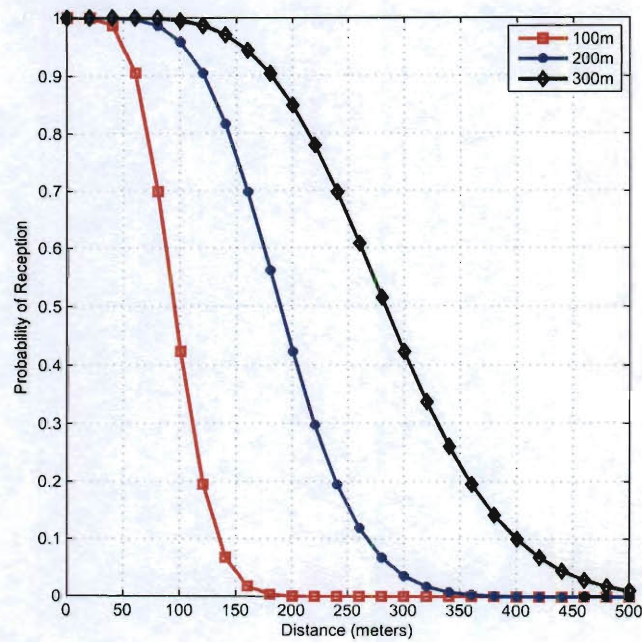


Figure 2.3 : Probability of packet reception for different intended communication ranges (in meters) and Nakagami parameter $m = 3$.

2.8 Related Work

In general, all prior work on cooperation can be categorized into two different areas, information theoretic and protocol development.

2.8.1 Theoretical Work

The pioneering research establishing the basis of cooperation can be traced back to the studies of Cover and El Gamal on the properties of the relay channel in 1979 [15]. From an information theoretic perspective, their work analyzes the capacity of degraded relay channels for the simple three-node topology consisting of a source, a relay and a destination. More recent studies by Laneman et al. [2, 10, 16] build upon this classical relay channel model by considering a fading channel and characterizing performance of spatial diversity techniques in terms of outage probabilities. In [10] the authors examine both amplify-and-forward (AF) as well as decode-and-forward (DF) techniques and develop outage regions with their associated outage probabilities to indicate how robust transmissions are at different SNRs. Further in [2] it is demonstrated that except for DF, every technique is capable of achieving full diversity, meaning that the outage probability decays proportional to $\frac{1}{SNR^2}$ instead of to $\frac{1}{SNR}$ as compared to the case where cooperation is not employed.

Practical applications of such diversity techniques were not considered until the term *user cooperation diversity* was first introduced by Sendonaris et al. in 1998 [17]. In this work, a capacity analysis of cooperative transmissions for mobile devices is performed. Furthermore, the same authors present a full system-level description of the concept of user cooperation in [3], and study the capacity of the system, as well as outage and coverage via an information theoretic analysis. In their work, they demonstrate that gains from user cooperation are substantial and that such increase

in data rates can be translated into reduced power for the users, which in turn extends the battery life of such mobile devices.

Additionally, there are many other studies (such as those performed in [6, 7]), on the outage probability corresponding to the different cooperation schemes as well as their fundamental capacity limits. Moreover, the tradeoffs incurred when cooperation is implemented are characterized in [5]. In this work by Lichte et al. ([5]), a closed-form solution for the expected aggregate interference caused by the k -closest nodes is derived in order to develop outage capacity equations for different cooperative schemes. In [14], Alamouti presents a relatively simple transmit diversity technique that uses two antennas at the transmitter and M antennas at the receiver. The technique introduced in [14] is proven to achieve the same diversity as maximal-ratio receiver combining. Alamouti's work is one of the techniques that make it possible to perform cooperative transmissions. Thus our analysis builds on top of this study.

Our work contrasts from the rest in the following way. First, none of the mentioned work investigates the effects of topological factors of a network on the performance that cooperation schemes are able to achieve. That is, they do not consider common topologies such as hidden terminals or information asymmetry, both of which are well known to significantly decrease link performance. Moreover, these studies only focus on rather simple topologies consisting of just a few nodes and do not consider large-scale networks where interference represents a major issue. Additionally, most models introduced use perfect geometry to characterize their interference regions, hence arriving at the formulation of rather unrealistic scenarios. In contrast, our work we deal with imperfect and more realistic channel realizations. Finally, prior work only compares cooperation to basic 802.11 or pure CSMA (simple non-cooperative schemes). However, other traditional techniques that are currently employed, also have the same

goal of improving reliability of wireless links (i.e. rate adaptation, multi-hopping, etc), and none of the related work has compared cooperation against such alternatives. Here we extend our evaluation and compare to two different non-cooperative techniques widely employed in commodity software against two cooperative protocols.

2.8.2 Protocol Development

Much of the prior work on cooperation has focused on developing protocols that take advantage of spatial diversity. In [4], the authors present a distributed on-demand cooperation protocol (DOC) that relies on the use of negative acknowledgments (NACKs) to distinguish between a corrupted packet due to fading or due to a collision. These NACKs will hence trigger cooperation only when needed. In our work we use DOC as one of the schemes used for comparison of performance. DOC had not been tested against more complex topologies or larger-scale ones and that is one of the focuses of this paper.

A Distributed Asynchronous Cooperation protocol (DAC) is introduced in [13]. In this work, the authors avoid the complex issue of achieving symbol-level synchronization by allowing multiple relays to schedule concurrent transmissions with packet-level synchronization. However, as with most of the prior work, we observe that this study does not deal with either different topology configurations or scenarios with more than three nodes.

Liu et al. [12] introduce the design for a medium access control protocol called CoopMAC where nodes experiencing high data rates assist those experiencing lower ones. Each source has the task of determining which node will be used as a relay to forward information. This decision is based on the amount of time it would take to transmit a given packet. Thus, the source will choose to either send a direct transmis-

sion or to forward data through some other user depending on which action takes the least amount of time. Contrary to our work, in CoopMAC orthogonalization is done in time. Therefore a transmission from the relay is done at a second time slot without any simultaneous transmission from the source. None of the mentioned prior literature has extended the implementation of cooperation to large-scale wireless networks, which is one of the main contributions of this work.

Chapter 3

Network Topology and Cooperation

Cooperative techniques in single flow topologies have been widely studied in [3–8, 10] among others. Such techniques have demonstrated their capability to decrease outage probabilities as well as bit error rates. However, the overall throughput performance of cooperation achievable in practice is not well known. Additionally, the behavior of cooperative schemes when more flows are involved is uncertain due to the increased complexity in the interactions among all nodes. The presence of an extra transmitter (i.e., a relay), can introduce further complications or alleviate some of the common problems in wireless networks. Due to increased spatial footprint and interference, the relay could negatively affect other flows in the network. However, in some cases, it could alleviate some of the problems caused by hidden nodes by passively informing other sources about transmissions that are currently taking place. Therefore, we dedicate this section to an extensive experimental evaluation of cooperation under the network topologies shown in figure 3.1, to explore this tradeoff. These topologies cover the cases of a single flow, fully connected network, hidden terminals, and information asymmetry.

3.1 Single Flow

First, we present the most basic network topology consisting of only one source and one destination (shown in Fig. 3.1 (a)) where cooperation is achieved by means of

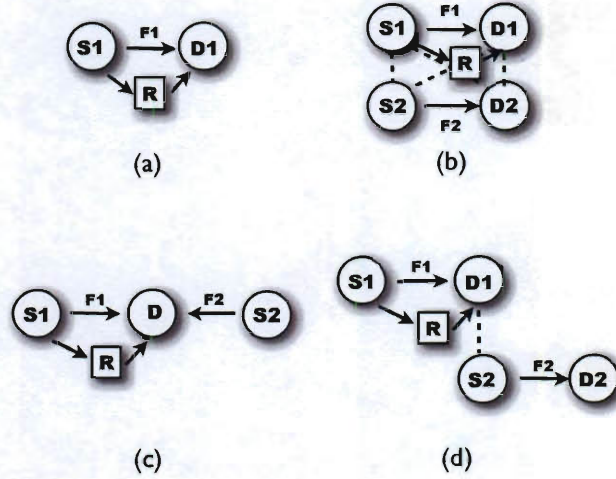


Figure 3.1 : Isolated study of cooperation in small-scale topologies. In the figure, circles represent sources and destinations, squares represent relays, arrows indicate traffic flows, and dotted lines indicate node connectivity. Each flow is labeled as either F1 or F2. Topologies are: (a) Single Flow, (b) Fully Connected, (c) Hidden Terminal, and (d) Information Asymmetry.

a relay assisting this single flow. The performance of this flow is mostly dependent on the quality of the channel as well as the distance between the source and the destination (issues which will be addressed in later chapters). We evaluate the performance of cooperation in an in-door environment with moderate fading where no interference is present. We expect cooperation to perform equally or better than the case of no cooperation, since the presence of the relay can only help when needed and not interfere with any other nodes. The evaluation of this single flow scenario is mainly with the purpose of verifying and validating our simulation results with those of the experimental platform. Furthermore, in order to calibrate the simulator to the parameters used in WARP we perform multiple runs to determine the thresholds required in the simulator in order to achieve the same packet delivery ratio (PDR) as

with the platform, for different received power values (as shown in Fig. 3.2).

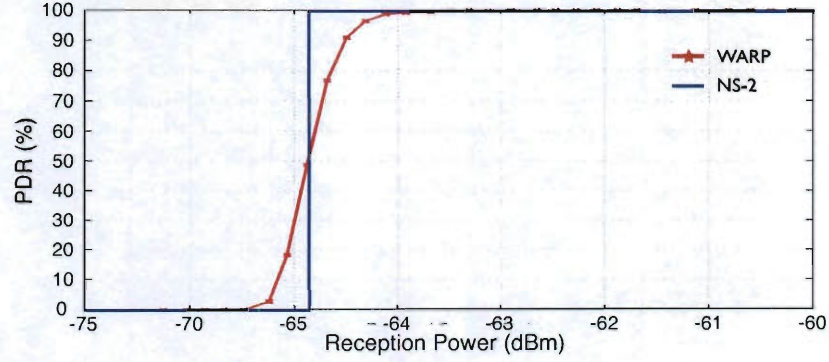


Figure 3.2 : Calibration of ns-2 with WARP

We use our modified version of DOC based on the WARP implementation presented in [4], to evaluate this cooperation protocol against no cooperation. In figure 3.3 we plot the throughput achieved by the flow with and without cooperation. Observe that the results from the experimental setup are very close to those from our simulations. Therefore, this result in part validates our implementation in ns-2. Moreover, notice a significant increase in throughput when cooperation is enabled compared to no cooperation. In average, throughput gains are on the order of 46%! Our evaluation also agrees with previous results demonstrated in the related work (e.g. [4]). Figure 3.4 shows a detailed timeline representation of how the employed cooperative protocols operate in this single flow network in both cases when we have a successful or a failed transmission. After considering a single flow scenario, we extend our analysis to topologies consisting of multiple flows.

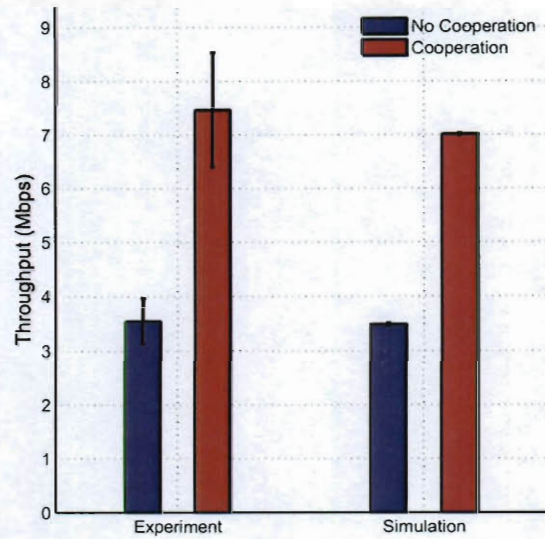


Figure 3.3 : Cooperation in Single Flow Topologies

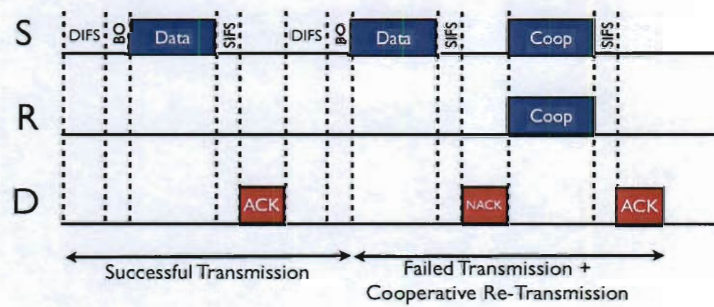


Figure 3.4 : Timeline for Single Flow Scenario

3.2 Fully Connected

We have demonstrated that cooperation achieves significantly high gains when employed in a single flow network topology. However, with cooperation, the presence of an additional transmitter introduces further issues such as an increase in the amount of interference in the network. For this reason, we evaluate the variant of DOC in a network consisting of two flows where all the nodes involved can carrier sense each other (see Fig. 3.1 (b)). For this setup, we only allow the relay to assist one flow at all times (i.e. flow 1). Further, we compare the results from our experiments to those found via simulations.

Observe in figure 3.5 that as expected, the throughput achieved by flow 1 is much higher when cooperation is enabled in both the experiments and the simulations. However, more importantly we notice that the performance of the competing flow is not affected by the activity of the relay. Since the source of flow 2 can hear the source of flow 1 at all times, and the relay only transmits whenever the source is supposed to transmit, then the competing flow will be already deferring to the cooperative flow (we will look at this issue into more detail in chapter 6). The relay is not taking any extra air-time other than the amount expected by other carrier sensing flows, therefore the fact that the relay is transmitting should not affect the others' performance at all.

In Figure 3.6 we present the timeline showing the interaction between the different flows in a fully connected network. It is important to notice that the use of NACKs is enabled for both flows. If this was not the case, then we would be dealing with fairness issues and a disadvantaged flow because only the cooperative flow would be having immediate retransmissions after receiving a NACK. However, by enabling NACKs in both flows, we make sure that the non-cooperative flow is also able to retransmit

immediately without backing off, or increasing its contention window (CW) after a failed transmission (notice this is not a comparison against pure CSMA).

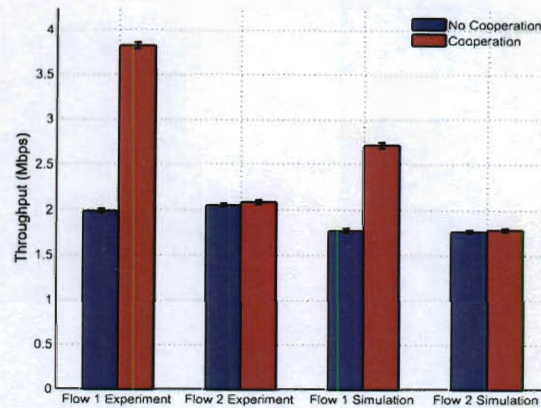


Figure 3.5 : Cooperation in Fully Connected Topologies

3.3 Hidden Terminals

A common topology that is observed in practice is the hidden terminal scenario. In this case (shown in Fig. 3.1 (c)) at least two different sources are trying to transmit to a common destination. However, even though the destination of one flow can hear both sources, the latter ones cannot hear each other. This means that carrier sensing will not be able to make any of them defer to the other therefore causing multiple collisions at the destination. This translates into a significant loss in performance for both flows. The use of a four-way handshake (by means of RTS/CTS) has been proven to decrease the magnitude of such negative effects. However, in a cooperative network, the presence of the relay could potentially alleviate this problem if its location would

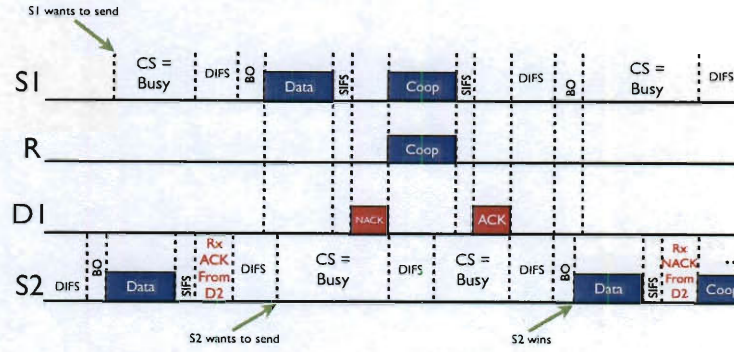


Figure 3.6 : Timeline for Fully Connected Scenario

allow for the different sources involved to hear this relay. For example, in Fig. 3.1 (c), if the source of flow 2 is able to hear the relay in a cooperative transmission, then it would defer to it, therefore decreasing the number of collisions.

In figure 3.7 we plot the throughput achieved by both flows with and without cooperation. Observe that just by enabling cooperation in flow 1, its throughput increases significantly. With cooperation, the relay will not only help deliver many more packets, but it will also let the other source know (implicitly through carrier sensing) that a transmission is in progress and it should defer to it. More importantly, notice that the throughput for the competing flow also increases. By positioning the relay wherever both sources can hear it, we provide the network with more knowledge regarding its overall state therefore leading to a decrease in the number of collisions. This in turn, increases the performance of both flows.

The timeline shown in Figure 3.8 depicts the case where a collision due to a transmission from both sources would yield a NACK only addressed to the source of flow 1 (S1). If the source of flow 2 (S2) is able to hear the relay, the cooperative retransmission triggered by the destination of flow 1 (D1), will cause S2 to defer to

the cooperative flow therefore avoiding a collision. Notice this situation is symmetric whenever the NACK caused by a collision would only be addressed to S2. However in this case, since S2 does not use the relay, S1 will not know it needs to defer to S2's retransmission. Therefore if S1 transmits, another collision will occur.

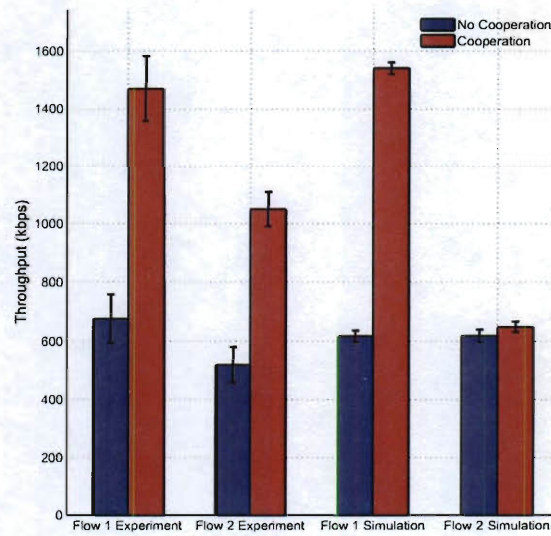


Figure 3.7 : Cooperation in Hidden Terminal Topologies

3.4 Information Asymmetry

Another common topology found in practice is the scenario of information asymmetry which is shown in figure 3.1 (d). In this scenario, two different sources (i.e. S1 and S2) transmit to two different destinations. However, S2 is within carrier sense range of the destination of the competing flow. Since the different sources cannot hear each other, they will not defer to one another thus causing collisions at only one of the

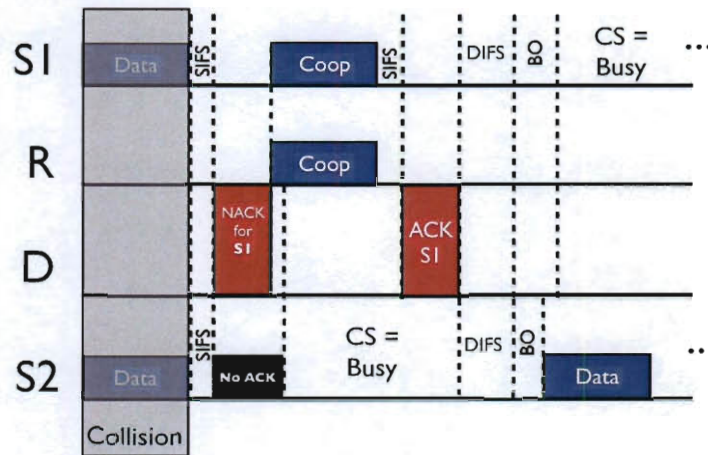


Figure 3.8 : Timeline for Hidden Terminal Scenario

destinations, namely D1. This leads to a case where we have a disadvantaged flow affected by the multiple collisions. Therefore, the performance of one flow (flow 2 in this case) is expected to be much higher than that of the competing one.

The presence of the relay could potentially diminish the negative effects at the disadvantaged flow if this is able to hear both sources, and vice versa. Such condition could happen because a transmission from the relay would cause the source of the competing flow to defer, hence decreasing the number of collisions. In this section we explore this issue and quantify its effects on both flows.

Observe in figure 3.9 that as expected, the difference in throughput between the advantaged and the disadvantaged flows is rather significant. However, we notice that even though gains from cooperation at flow 1 are high (approximately 55%), its performance is still rather unsatisfactory compared to that of flow 2. Several different cases explain the behavior of this network:

- *Preamble is not successfully received at the destination.* If this happens, a NACK

will never be sent and therefore, cooperation will never be triggered. This means that the source of flow 2 will not defer to the cooperative flow, thus leading to the same natural behavior of information asymmetry topologies. This case is the most common one because the amount of time spent by the second flow doing backoff is very short. Consequently, the likelihood of a preamble arriving at D1 while S2 is not transmitting (sent from S1), is small. This first case is depicted in figure 3.10.

- *Preamble successfully received, failed payload, and relay is carrier sensed by S2.* A collision at D1 triggers a cooperative retransmission. If S2 is able to hear the relay, it will defer to it therefore preventing a collision at D1. This is the case that provides flow 1 with an opportunity to successfully transmit a packet after a cooperative retransmission. This case is shown in figure 3.11.
- *Preamble successfully received, failed payload, and relay cannot be carrier sensed by S2.* A collision at D1 triggers a cooperative retransmission. However, since S2 cannot hear the relay, it will transmit therefore causing another collision. This case is shown in figure 3.12
- A final case occurs whenever a collision happens at D1 and this node is not able to resolve it for the entire length of both packets. Then, by the time the collision is resolved and the destination is able to act upon this, a timeout and retransmission by S1 or a transmission by S2 will cause another collision.

Findings: Cooperation can vastly improve the throughput performance of single flow scenarios. However, as we consider multiple flow topologies, the presence of the relay not only could improve the throughput of the assisted flow, but also contribute

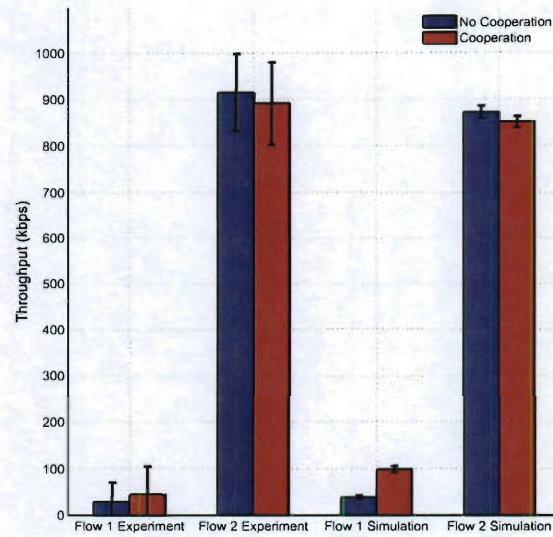


Figure 3.9 : Cooperation in Information Asymmetry Topologies

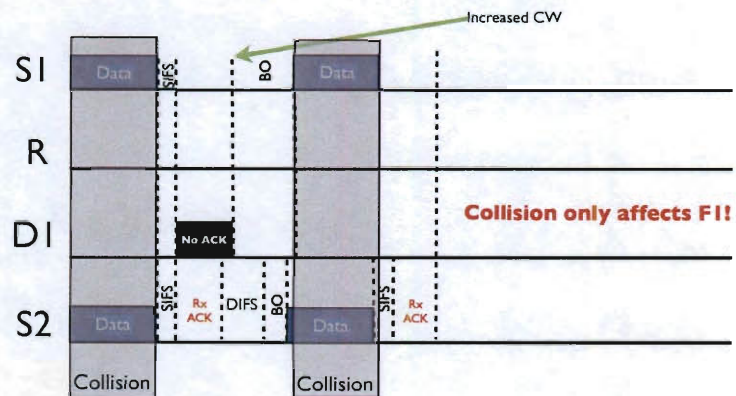


Figure 3.10 : Information Asymmetry Case 1 - Bad Preamble

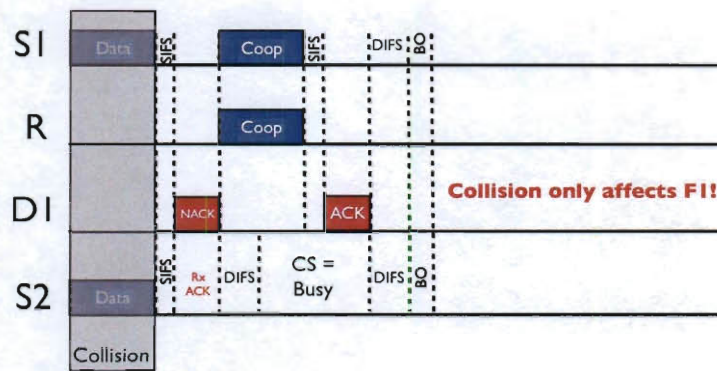


Figure 3.11 : Information Asymmetry Case 2 - Good Preamble, Bad Payload (Relay Carrier Sensed by Competing Flow)

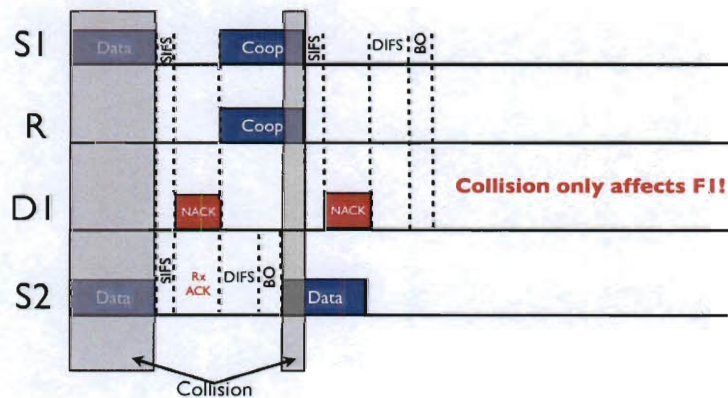


Figure 3.12 : Information Asymmetry Case 3 - Good Preamble, Bad Payload (Relay Not Carrier Sensed by Competing Flow)

to increasing the knowledge of the overall state of the network. This could potentially lead to a more balanced resource allocation among the different flows in the network, which translates into adding coordination that would eventually lead to an increase in performance. In the scenarios we have just studied, the presence of the relay provides other flows with more knowledge (in a passive way) about the overall state of a network. However, if we could further allow the relay to actively provide this information to neighboring flows, then we could alleviate the problem of collisions even more.

Chapter 4

Cooperation vs. Rate Adaptation

Cooperation is a technique aimed at improving link reliability by adapting to the quality of the channel. Likewise, modulation and coding rate adaptation are techniques that have been used traditionally to overcome unreliable channel conditions caused by fading and multipath. In rate adaptation, a transmitter adjusts its coding modulation rate according to channel fluctuations induced by either transmitter's or receiver's mobility, as well as scatterers [19].

Ideally, all rate adaptation protocols select the highest possible rate that guarantees a successful transmission, however the mechanisms used to accomplish this vary from one protocol to another. In general, channel fluctuations are addressed by these protocols in one of two ways [19]. In loss-triggered adaptation, the transmitter makes a decision for adjusting its rate based on the number of failed or successful packets. In SNR-triggered adaptation however, the transmitter via a four-way handshake is informed of the signal-to-noise ratio of the last transmission and adjusts its rate accordingly.

Unlike cooperation protocols, rate adaptation is widely implemented in existent commodity software and hardware [20]. Consequently, we pose the question of whether cooperative schemes are capable of outperforming rate adaptation protocols or not. The answer to this question could have considerable impact on the way we currently deal with channel induced performance degradation.

In this section we present a comparison of the *ideal cooperator* protocol, against an implementation of an SNR-triggered rate adaptation protocol. In this rate adaptation scheme, the transmitter adjusts its rate based on information obtained from the CTS sent by the destination. We have added a field to the structure of the CTS packet so that it contains the SNR with which it was received at the source. Hence, based on this SNR, the source dictates which modulation rate will be used to transmit the next MAC Protocol Data Unit (MPDU). We simulate a three node network consisting of a source, destination, and a relay, where the source and destination are 150 meters apart from each other. The relay is only active in trials where cooperation is enabled. Thus, for the rate adaptation scheme, only a direct transmission is considered.

Figure 4.1 (left) presents a comparison of the absolute throughput achieved by the rate adaptation scheme and cooperation for both 16- and 64-QAM. For low transmission power (< 8 dBm), rate adaptation performs approximately the same as cooperation at 16-QAM. Moreover, at this same interval, basic 802.11 (No Relay) is outperformed by both schemes. However, as transmission power is increased beyond 8 dBm, three different trends are observed. First, the difference between direct transmission and cooperation at 16-QAM decreases until both curves are the same. This occurs because with increased power at the transmitter, the relay is no longer needed (for that specific modulation rate) and a direct transmission suffices. Second, a tipping point is reached at approximately 14 dBm, where power is sufficiently high so as to increase the probability of packet reception therefore allowing the reliable use of higher rates. Finally, the performance of rate adaptation degrades with increased transmission power. The reason for this is the inaccurate selection of modulation rate. As channel quality improves, previously appropriate rate becomes underselected. Observe for example in Figure 4.1 (right) that for higher power even

though the ideal rate would be 64-QAM, the protocol still transmits packets at both QPSK and 16-QAM. Furthermore, this last result agrees with those observed in [19] for SNR-based rate adaptation schemes. Notice that a combination of rate adaptation and cooperation would yield maximum throughput for every transmit power.

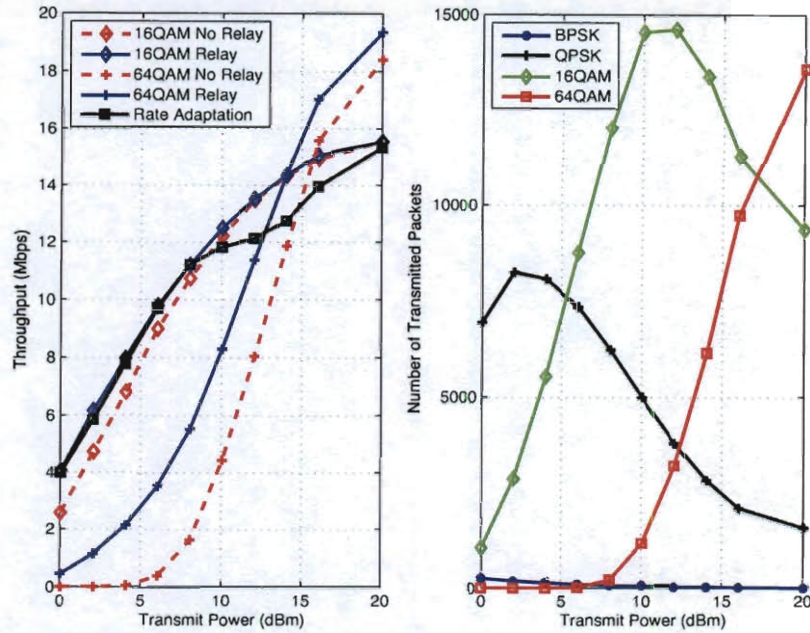


Figure 4.1 : Comparison of rate adaptation against DOC at different modulation rates.

From the previous results, we observed that the difference in performance between a cooperative scheme and basic 802.11 is highly dependent on the modulation rate used for the payload (preamble is fixed at base rate). Therefore based on this observation, in figure 4.2 (left) we plot cooperation vs basic 802.11 for different rates. As modulation rate increases, the difference in throughput between a cooperative scheme and a non-cooperative one increases as well. This means that for the regimes we are

operating at (i.e. specific distance and transmit powers used for this evaluation) for rates such as BPSK and even QPSK, cooperation does not provide any gains; since packets are more likely to successfully arrive due to the lower rate used, no assistance from the relay is needed. However, no losses are observed either. To help us verify this result, we plot in figure 4.2 (right) the number of cooperative packets that are triggered at each modulation rate. From the graph, observe that cooperative transmissions occur mostly at the higher 16- and 64-QAM modulation rates; while, cooperative transmissions occur rarely, if at all for the lower rates. These results demonstrate that if we are operating at lower rates there is no need to waste any resources trying to find the best relay, or even replying with NACKs. Moreover, if cooperation requires the relay to perform extra tasks that utilize some of its resources such as energy, if we operate in these regimes, we could avoid such unnecessary actions.

Findings: Rate adaptation and cooperation techniques could potentially be combined to provide higher throughput performance. However, the rate adaptation protocol needs to account for possible under or overselection as demonstrated in [19]. Moreover these protocols need to be aware of when cooperation should be triggered based on the rate used so as to not waste fundamental resources such as energy or air time utilization.

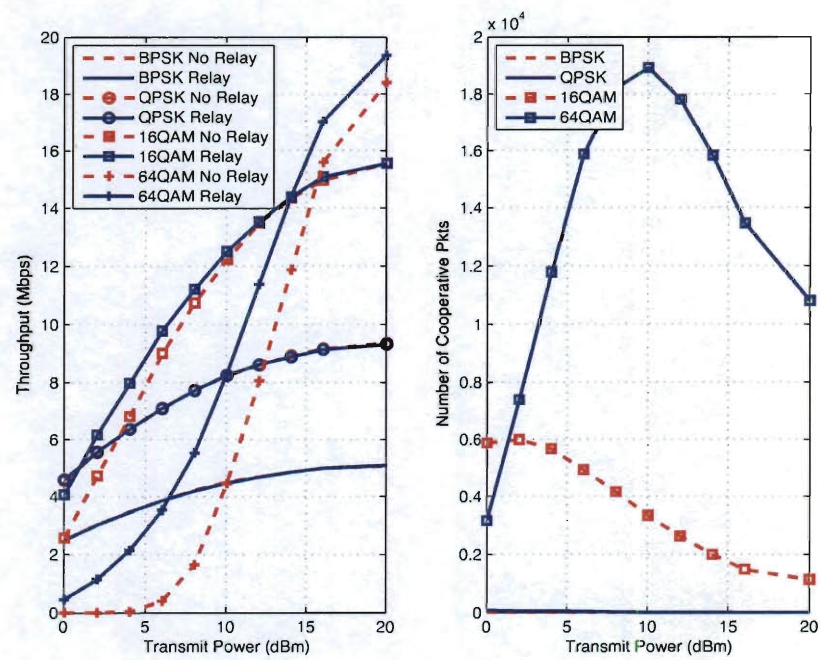


Figure 4.2 : Comparison of basic 802.11 against DOC at different modulation rates.

Chapter 5

Influence of Source-Destination Separation on the Performance of Cooperation

Path loss represents one of the strongest factors affecting signal attenuation in a wireless transmission. As the source-destination separation increases, the likelihood of successfully receiving and decoding a direct transmission decreases as described by all models considering path loss such as Nakagami [21]. However, the presence of a neighboring node within range of both the original transmitter and receiver, could potentially diminish those effects by either *i)* taking advantage of diversity and transmitting two copies of the same signal hence enabling cooperation and increasing reliability of each transmission, or *ii)* routing the packet in a multi-hop, store-and-forward type of transmission.

Ideally, at short source-destination separation we expect cooperation to have little, to no effect on throughput compared to a direct transmission using basic 802.11. The reason being that packet losses due to channel fading are rare, since signals arrive at the destination with strong power. On the other hand, if the relay is used to store-and-forward packets in a two-hop path at short distances, we expect throughput performance to be lower because the relay becomes unnecessary and a direct transmission would suffice. Nevertheless we expect to see all these protocols outperform basic 802.11 as we reach a certain range, this is due to the inability of a direct transmission to reach the destination because of increased propagation distance.

Moreover, if source-destination separation is very large (i.e. to the extent that

the relay cannot hear either the source or destination), cooperation protocols simply reduce to basic 802.11 which leads to a complete loss of the link. This is due to the relay not being able to decode the original transmission from the source or the NACK from the destination, thus never triggering cooperation.

In this section we evaluate the tradeoffs of using cooperation against static routing or direct transmissions as propagation distances vary. We perform thousands of simulations where we vary not only this source-destination distance, but also the location of the intermediate node with respect to the flow. We simulate a UDP transmission in ns-2 between a source and a destination where we sweep over different separations (from 0 to 500 meters). At each distance we randomly position 1000 potential relays that are uniformly distributed inside a circle having the source and destination nodes at opposite extremes on the circumference. Each relay position represents a single simulation, and our results report the throughput achieved by the best performing relay. We find this relay by brute-forcing across all the different possibilities.

We measure absolute throughput as well as percent throughput gains as a function of source-destination separation and plot our results in Figure 5.1. Further, we compare the *ideal cooperator* scheme with our variant of DOC, as well as a forced two-hop routing protocol. Note that throughout the rest of this section we will refer to the variant of DOC as just “DOC.” Since there is only one flow involved in this evaluation, no collisions are expected, hence such variant of the protocol behaves exactly like the original DOC does. For comparison purpose, we use direct transmissions with basic 802.11 (i.e. RTS/CTS disabled) as our baseline.

At small distances (up to 50 meters), observe that there is no significant performance difference between the cooperative protocols and basic 802.11 due to the proximity between the source and the destination for the reasons described above.

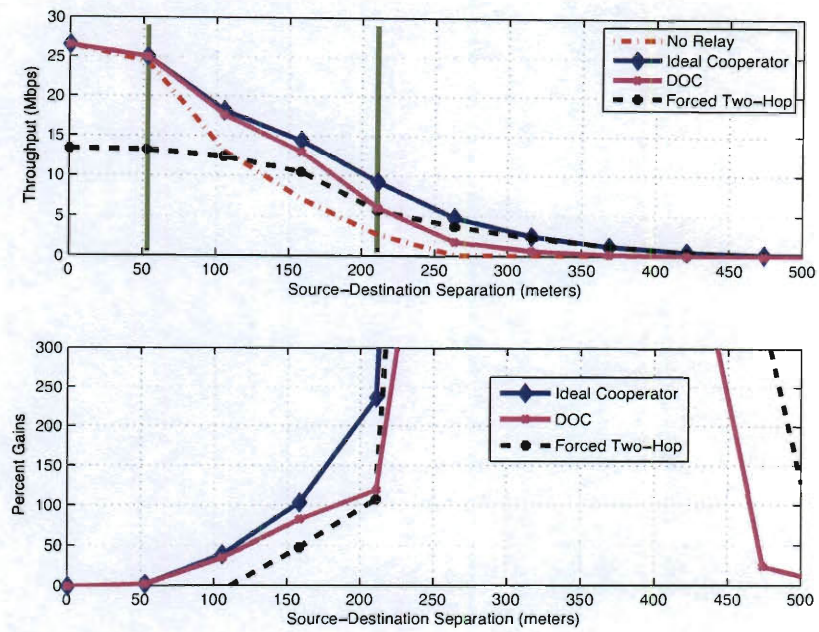


Figure 5.1 : Top plot shows absolute throughput attained by the different protocols. The vertical bars enclose the ranges at which both cooperation protocols outperform all other transmission techniques presented. Bottom plot displays throughput percent gains compared to basic 802.11 (No Relay).

More importantly, since these cooperative schemes only assist when signal power at the receiver is below a decode threshold, at worst, they perform the same as basic 802.11.

At moderate distances (between the green vertical lines), both the *ideal cooperator* protocol and DOC outperform basic 802.11. While an increased source-destination separation distance reduces the success rate of a direct transmission, having a node in between mitigates this negative effect. Since packet preambles are sent at base rate while the payload is sent at a much higher rate (i.e. BPSK vs. 64QAM), the likelihood of receiving the preambles can be much higher even at longer distance ranges. Hence, the rather low power signal from the source's retransmission combined with that of the relay, will allow more packets to arrive at the destination. Furthermore, it is at moderate distances as well, that we observe a cross-over point where forced two-hop routing begins outperforming our baseline. At that point, it is clear that an intermediate node forwarding data is necessary in order to mitigate the fast rate of decay in throughput performance.

Finally, at larger distances, we encounter a tipping point (i.e. approximately 210 meters) where multi-hopping begins outperforming DOC, even though most relay transmission occur near that point (2000+ packets for both cooperation protocols). This happens because more time is wasted in retransmissions, and even though we are performing better than 802.11, multi-hopping does not require as many retransmission, thus achieving better performance. For even longer separation, preamble arrivals increasingly fail, therefore, no NACKs can be sent in order to trigger retransmissions at the relay.

Also notice that up to around 130 meters (short to moderate distance), DOC achieves “best” performance; its achieved throughput mimics that of the *ideal co-*

operator protocol for those ranges, meaning that it cooperates every single time a cooperative transmission is necessary. However, on the other hand, for very long distances, multi-hopping mimics the *ideal cooperator* protocol, meaning that it becomes the optimal solution since it allows packet forwarding with 100% probability.

To visualize the gains from cooperation and multi-hopping compared to a direct transmission, we plot percent gains of such schemes in the bottom graph. These results show that a separation of at least 75 meters, yields considerable gains of approximately 25% for both cooperation protocols. Finally, when the link between the source and the destination is almost nonfunctional, cooperation can achieve up 1000% gains. As expected, multi-hopping achieve more than 2000% when a normal 802.11 link is almost completely unusable.

Findings: Regardless of the distance between a source and a destination, a NACK-based cooperation protocol performs at least as well as basic 802.11. Furthermore, It is only at large distances where multi-hopping becomes a better option since it might only require two transmission phases (whereas cooperation requires three phases since it has to wait for feedback from the destination) in order to be able to successfully transmit a packet to the destination.

Chapter 6

Impact of the Relay's Spatial Footprint on the Network

The position of the relay with respect to the assisted flow is critical to the performance gains that can be achieved through cooperation. Since the relay has to be able to decode both the original transmission from the source as well the cooperation trigger from the destination, its location should be one such that it can hear these two nodes. Likewise, the position of the relay with respect to surrounding flows is also critical to the performance of those competing flows.

Consider the topologies in figure 6.1. Case (a) presents a fully connected network where the relay only assists flow 1. In this scenario we expect the cooperative flow to outperform the other one due to an increased number of successful transmissions. However, we do not expect a decrease in performance of flow 2 because the relay's transmission occurs simultaneously to that of the source. Therefore, the relay does not incur in any extra channel utilization.

On the other extreme, case (c) consists of a topology where neither flow interferes with each other. The relay activity does not have any influence on the operation of flow 2; hence, we achieve a perfect decoupling where the channel is not shared and no flow defers to the other. Now, consider scenario (b) where only the relay can hear both flows. In this case, the presence of the relay can negatively affect the operation of flow 2. This might happen because the relay is now interfering with the competing flow every time a cooperative transmission is triggered. Therefore, the channel instead

of being available only for flow 2, now has to be shared with the relay transmissions. More importantly, there could be a scenario where the relay might not be able to significantly help flow 1 but it is still interfering with flow 2, thus leading to low gains from cooperation for flow 1 at the same time as it degrades the performance of flow 2.

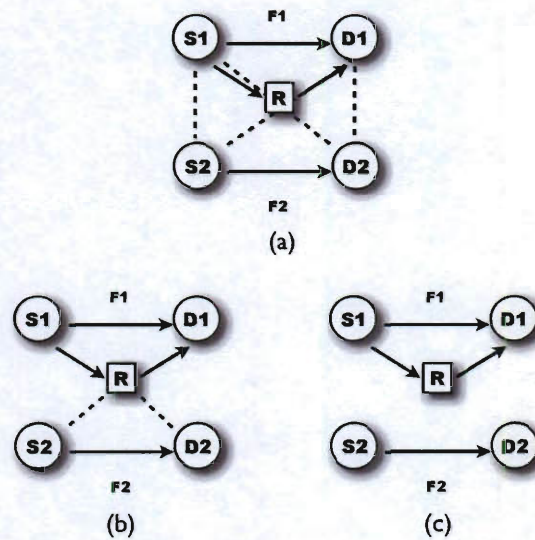


Figure 6.1 : The figure depicts three different two-flow topologies where a relay assists only one flow. Solid lines represent actual flows while dotted lines indicate node connectivity. Case (a) presents a fully connected network. Case (b) shows a case where only the relay is heard by the second flow. Finally case (c) portrays a topology where both flows are completely decoupled

In this section, we quantify the effects that the increased transmission footprint due to the activity of the relay, has on other flows in the network. We evaluate these effects via simulations in ns-2 with the purpose of understanding the regimes under which cooperation can improve or degrade the overall performance of a network consisting of more than one flow. Specifically, we focus on three different scenarios: *i)* two-flow scenario with coupled flows, *ii)* two-flow scenarios with uncoupled flows,

and *iii*) large-scale networks with multiple flows spanning everything from isolated to fully connected topologies.

6.1 Two-Flow Coupled

First, we study a two-flow topology where both flows are coupled due to their relatively small separation distance (100 meters), hence yielding a fully connected network. For each of these competing flows we let the sources and destinations to be 175 meters apart. We allow one cooperative relay to assist only one of the flows (i.e. flow 1) in order to analyze its influence on the competing flow (i.e. flow 2). We ran 400 simulations, each lasting 60 seconds. Each simulation consisted of a different position of the relay inside a square grid while we kept both sources and destinations fixed in their respective positions. For this study we evaluate the *ideal cooperator* protocol in order to study the extreme case where the relay always cooperates as long as it receives the original packet from the source for multiple relay locations. Using this protocol provides us with a potential “worst-case scenario” for neighboring flows, while providing a “best-case scenario” for the assisted flow. Due to the working principles of such protocol, we expect gains to be highest when the relay is closest to the destination. This is very intuitive since both NACKs and original data transmission are always received, hence by having the relay near the destination we are also increasing the likelihood of a retransmission from the relay to arrive with nearly 100% probability.

In figures 6.2 (c) and (d) we plot throughput gain/loss as a function of the relay position across the grid for both flow 1 and flow 2 (compared to basic 802.11) respectively. From (c) observe that if a cooperative protocol is smart enough as to cooperate every time it is needed, then gains can be in the order of 200%. More importantly,

as we had argued, (d) demonstrates that cooperating with flow 1 does not seem to have any significant effect on the performance of flow 2. Hence, we can conclude that the relay is not consuming any extra channel resources than those that flow 1 would consume if its path to the destination was relatively good and no relay was present.

Furthermore, notice that the best-case scenario can significantly improve the performance of the cooperative flow whereas the worst-case scenario does not have any considerable effect on the competing flow.

6.2 Two-Flow Uncoupled

We now focus on the case where neither flow can hear each other thus leading to both of them having their own channel resources without having to contend in order to transmit. For these simulations, we use the same setup as for the coupled flows scenario except that now both flow are 700 meters apart from each other.

In figures 6.2 (a) and (b) we plot throughput gains/losses as a function of the relay position for both flows. Observe in (a) that for flow 1, gains can again reach up to 200%. However, notice in (b) that as the relay starts to move away from the assisted flow, it begins affecting the competing flow. These results show that such degradation could reach up to -40% throughput losses for the latter one.

Even though we are unrealistically allowing the relay to send and receive packets at ranges where it certainly could not in reality, this shows the worst-case scenario of how the relay could potentially degrade the performance of neighboring flows. Although we do not expect the relay to be hearing flow 1 at such long distances, we know that there still is a possibility that a scenario like that of figure 6.1 where both flows are closer but still cannot hear each other while the relay can, could appear in real networks. If this happens, the relay might get to a point where it is not helping

the cooperative flow much but it is still causing significant interference on neighboring flows.

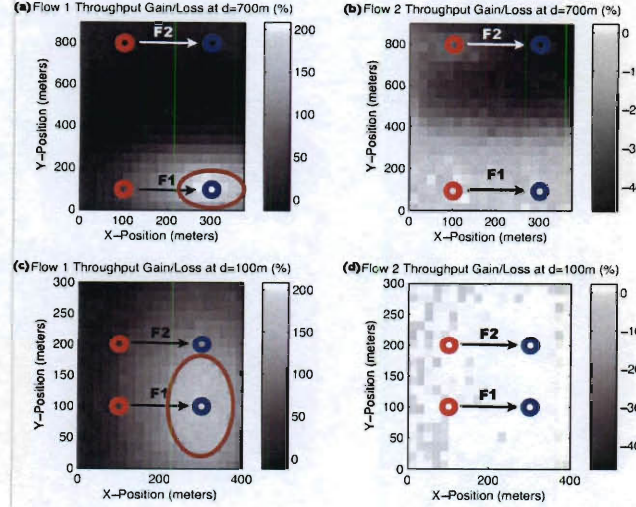


Figure 6.2 : Influence of Relay's Transmission Footprint in Coupled and Uncoupled Flows

6.3 Large-Scale Networks

We have just observed that even when considering only two flows, the fact that a cooperative relay is assisting one of them can significantly (and adversely) impact the performance of the other flow. Therefore, if we would extend our analysis to large-scale network scenarios where multiple flows interact in many different ways (i.e. coupled/uncoupled flows, etc), we would expect the presence of relays to cause similar effects to those observed for smaller topologies on the performance of the overall network. Furthermore, the increased number of sources contending for the channel, as well as the random node location and the interactions among them lead to a combination of behaviors such as those we have seen so far throughout this work.

In this section, we extend our analysis and simulations to multi-flow topologies consisting of 20 flows. The simulation setup is the following: We position 500 nodes in a 1000x1000 meter square grid. Out of the 500 nodes, we randomly select 20 of them to be the sources (from a uniform distribution). Each source then randomly selects one destination that is within a maximum distance range*. This distance is chosen based on the results obtained from figure 5.1 in order to consider regions up to where either cooperative protocol or static routing are still able to achieve some gains. Finally, each flow at random selects a relay that is also within a certain distance from both the source and the destination. This guarantees we always select a relay that is inside the circumference where the source and destination are located at opposite sides. Such topology allow us to have network configurations spanning everything from independent flows to fully connected scenarios.

To study the effects caused by the increase in transmission footprint due to co-operation, we compute the time in between packet transmissions for each one of the flows. Since we allow all sources to be fully backlogged, the application layer will keep passing packets to the lower layers without any wait in between. Therefore, the rate at which packets leave each source node will depend on MAC and PHY behavior. Contention and interference will dictate such behavior based on carrier sensing mechanism as well as the influence of neighboring flows in the network. For this reason, we measure the time in between such transmissions and use it to analyze the amount of contention present in the network. We expect that the longer the time between each packet transmission, the higher the contention is. In figure 6.3 we plot the average packet inter-transmission time per-flow. Observe that in average, the inter-transmission time is much lower in basic 802.11 (no cooperation). However, for

*We used 350 meters for the results we present here.

both cooperation protocols the results are higher (approximately 20 ms in average). This means that the presence of the relay causes extra interference that leads to increased contention in the network.

Moreover, in figure 6.4 we plot per-flow throughput for each of the already mentioned schemes as well as overall network utility. Notice that although we are increasing the amount of interference in the network, both cooperative protocols still achieve some gains compared to basic 802.11. However, these gains are rather small and do not provide with a significant increase in performance.

With respect to the network utility, in this work we define it as:

$$U(f) = \sum_{j=1}^n \log(f_j) \quad (6.1)$$

where f_j is the rate of flow j and n is equal to the number of flows in the network (which in this case is 20). As with throughput performance, network utility for both cooperation protocols only shows a very slight increase. This is just demonstrating that the increase in throughput due to cooperation is too small that it does not provide any benefit to the network in terms of quality of service (QoS).

Findings: Location of the cooperative relay is crucial to determine not only the gains obtained from cooperation but also the adverse effects caused on surrounding flows due to interference. That is, when we have coupled flows no negative effects are observed, however, with uncoupled flows the relay could significantly affect a neighboring flow. In large scale networks the gains that had been observed in small-scale topologies are not there anymore and one reason for this is the increased contention due to extra interference from the relay. Consequently, when designing cooperation protocols, a wider view of the network should be considered in order to minimize the negative impact due to such increase in transmission footprint.

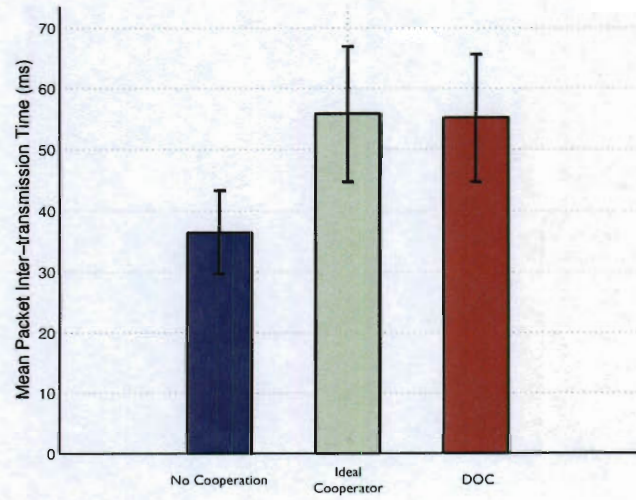


Figure 6.3 : Mean Packet Inter-Transmission Time

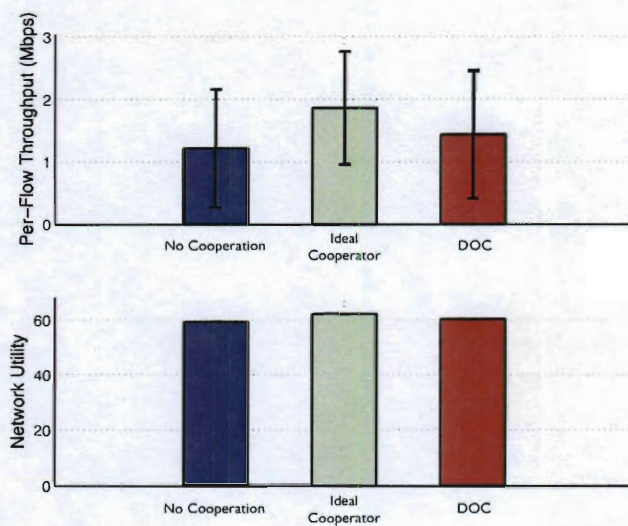


Figure 6.4 : Per-Flow Throughput and Aggregate Network Utility For Large Scale Scenarios

Chapter 7

Cooperation in Multi-Hop Networks

Up to this point we have restricted our analysis to cases where the destination is at most one hop away from the source. Moreover, we have considered multi-hopping routing as an alternative to cooperation and even compared them side to side in order to understand under which regimes one outperforms the other. However, as we move away from atomic scenarios into more complex networks such as ad hoc and mesh networks, we realize that these two techniques rather than compete with each other, might be used to complement one another. Therefore, in this section we look into this option of having a hybrid network taking advantage of both routing and cooperation at the same time.

First, we analyze the most basic multi-hopping scenario where we have a linear topology consisting of 7 hops (Figure 7.1). Looking at such basic configuration will help us understand some of the behaviors observed in more complex networks. We then focus on ad hoc networks where no fixed infrastructure exists, and the location of the nodes is completely random. Finally, we extend our study to investigate the effects of cooperation on a mesh network that is based on the existing TFA network located in a community of Houston, TX.

7.1 Linear Topology

One of the most basic types of multi-hop networks we can find is a linear topology. It is well known that in this scenario, as the number of hops is increased, the throughput performance decays relatively fast specially on the first hop. This happens due to many factors such as lack of information at each node with respect to the state of the rest of the network, hence leading to scenarios where hidden terminal are present for example. Such fast decay in performance leads to full outages where after a given number of hops, throughput is practically null. In multi-hop scenarios, we often find a high density of nodes that could help not only to route packets in a store-and-forward way from a source to a destination, but also to enable cooperation and hence try to achieve higher performance.

Taking these two last statements into consideration, we expect that by taking advantage of those potential relays, we could be able to not only increase per-hop throughput but also reach farther hence making that last hop functional.

To study the performance that results from the interaction between cooperation and multi-hopping routing, we create linear topologies consisting of one single source such as the one depicted in figure 7.1, where all nodes are 175 meters apart from their neighbors. We evaluate the performance of cooperation compared to basic 802.11 for different network sizes (i.e., from 1 to 7 hops). Our results show averages over 10 simulations for each network size.

Figure 7.2 presents absolute throughput for both schemes (top plot), as well as percent throughput gains (bottom plot). Observe that regardless of the size of the network, throughput is always higher with cooperation. However, the rate of decay of cooperation is also higher than that of our baseline. As the number of hops increases, both schemes approach zero throughput. Notice that once we reach four hops, the

performance of basic 802.11 is practically null. However, cooperation is still able to provide with a throughput on the order of 700 kbps. The fourth hop is also the one that marks a significant change in the slope of the gains achieved through cooperation. This happens because after this point, basic 802.11 is relatively nonfunctional and only through cooperation we observe a working link.

Finally, as we deal with flows consisting of approximately 7 hops, 802.11 performs so bad that gains achieved are as high 1150%! We know these gains are so significant just because of the fact that the baseline protocol is extremely bad and not because cooperation is performing exceptionally well. However, this means enabling cooperation can help us keep certain links alive which can be very useful in networks where that last hop is necessary.



Figure 7.1 : Basic Linear Multi-Hop Topology

7.2 Ad Hoc Networks

In contrast to simple one-flow, one-hop topologies, performance of multi-flow networks depends on a combination of multiple factors such as node separation, channel characteristics (e.g. fading and multi-path), and interference, among others. Furthermore, we expect that employing multiple relays for cooperation would heavily increase the amount of interference in the overall network. So far we have considered each one of these factors individually as key elements affecting the performance of

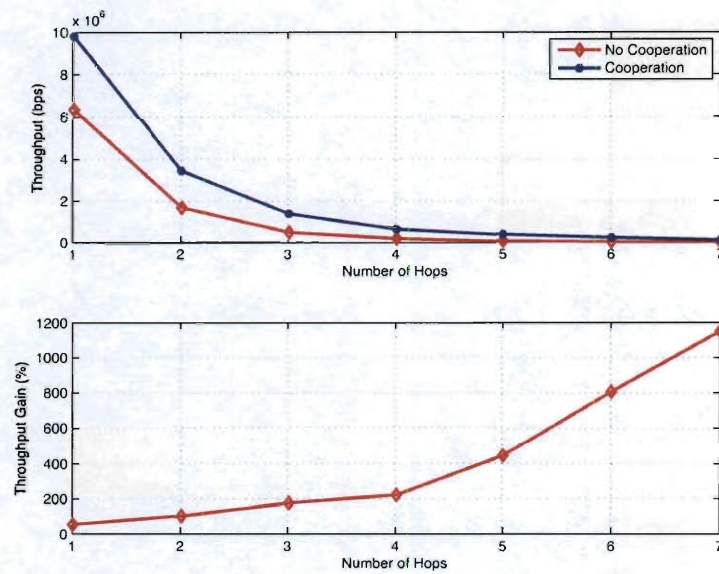


Figure 7.2 : The top plot presents absolute throughput as we vary the number of hops participating in the network. The distance between nodes is always the same at each hop. The bottom plot shows throughput percent gains attained by cooperation, compared to basic 802.11, as we vary the number of hops in the topology

cooperative techniques. In this section we incorporate all these factors into a single type of scenario by extending our analysis to large-scale ad hoc networks featuring up to 20 different multi-hop flows. We model 20 constant-bit-rate (CBR) connections where nodes have a fixed location; we then report average throughput performance from 15 different simulation runs across a variety of topologies. These scenarios were generated by randomly positioning 20 flows inside a 1000x1000 meter area. Each source-destination pair can consist of a single-hop link or a multi-hop connection spanning from 2 to 4 hops depending on a random selection based on a uniform distribution. Thus, for example, the number of single-hop flows is expected to be different across all 15 scenarios. Each source and forwarding node counts with at most one relay to assist with cooperative transmissions when cooperation is enabled. For packet routing, we implemented a static routing scheme that chooses its path based on the distance between nodes and their relative location to one another (i.e. only nodes in between the source and the destination are chosen).

We use throughput as our performance metric as well as throughput gain. Since we expect performance to be rather different across flows consisting of different number of hops (based on the results observed in the linear topology), we look into each case separately.

The results in figure 7.3 support our arguments; As expected, the amount of interference added to the network has a significant impact on the gains achieved from cooperation. In figure 7.2 we had observed rather high gains even up to 4 hops. However, as we introduce additional flows, we observe these gains decrease to at least half of their original values on each of the cases. This situation occurs due to the combination of having more sources trying to transmit simultaneously therefore leading to deferrals, plus an increase in transmission footprint caused by the presence of the

relay. Notice that although gains are not the same once we increase the number of flows, no losses are observed. Therefore, even in these types of scenarios, performance of cooperation is at least as good as that of the basic 802.11 protocol.

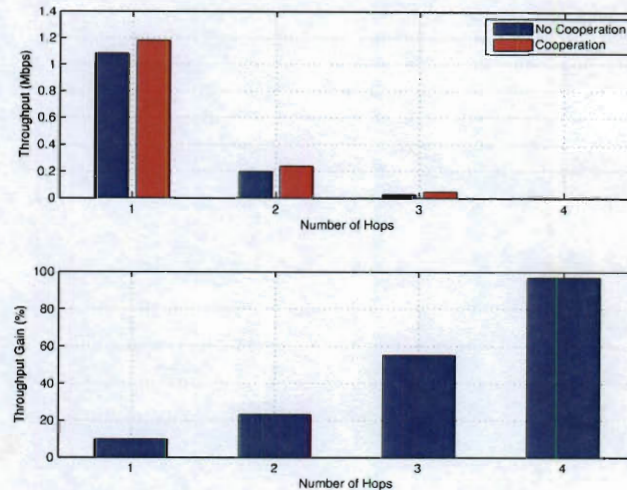


Figure 7.3 : Absolute throughput (top), and percent gains (bottom) for flows consisting of up to 4 hops. These results exhibit a similar trend to that of the simple linear topology even as we account for interference from other flows.

7.3 Mesh Networks

When analyzing operational networking environments, mesh topologies represent a key scenario to consider. In ad hoc topologies such as the one we presented in the previous section, user locations as well as their interactions are rather unpredictable. For the most part, there is no fixed infrastructure and therefore, no network design is involved at the moment of their deployment. However, deploying mesh networks involves a rigorous and structured planning process in order to guarantee a certain level of performance. This means that access points (APs) and gateways are positioned

in a way such that they are able to communicate with each other while maintaining relatively strong connectivity.

As we have seen before, cooperation techniques improve performance of weak, unreliable links. Thus, we expect little to no gains from cooperation when it is enabled for backhaul links that are already expected to perform at a certain level. For that reason, we study the performance of cooperation in both uncertain and sudden links between clients and APs, as well as planned backhaul connections among APs and gateways.

We emulate the TFA mesh network deployed in Houston TX (shown in figure 7.4) in ns-2. We position all APs according to their actual locations in the real network, and randomly generate up to 25 users that are within 250 meters from at least one AP. Moreover, we randomly select dedicated relays to assist both the APs and the clients with their transmissions whenever cooperation is enabled. We assume these relays are other users in the network that are not actively transmitting or receiving any data of their own. The network consists of a total of 15 APs conforming the backhaul and one gateway acting as a sink (i.e., connection to the Internet). A total of 25 nodes are mobile stations generating CBR traffic at 54Mbps (64-QAM). Additionally, packet forwarding among all nodes is done via static routing.

We model each AP and gateway according to the real network implementation. That is, based on results from previous measurements on the network, we create a model that takes into account the gains at each antenna depending on their angle with respect to other AP nodes. All APs consist of a single omnidirectional interface operating at 2.4 GHz, with the exception of the gateway and one AP which feature multiple interfaces (i.e., 2.4 GHz for the omnidirectional link and 5 GHz for a directional link connecting both). Each client transmits at 15 dBm which is the typical

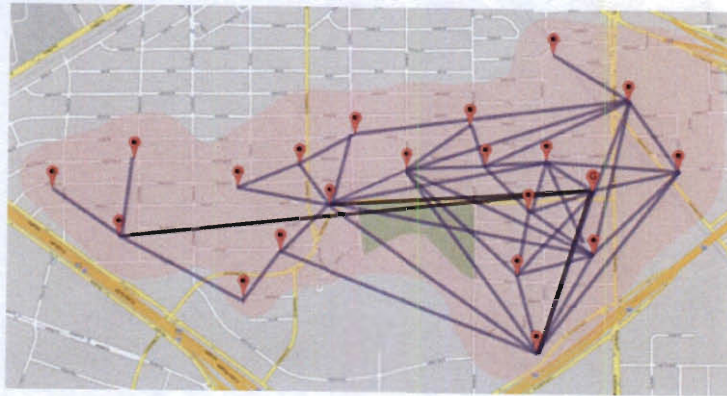


Figure 7.4 : TFA Network - Black dots represent each one of the APs, and each line denotes connectivity among these nodes.

transmission power of notebook computers with WiFi cards. However, all APs transmit at a power of 23 dBm as specified in [22]. Further, we modify the carrier sense and receive thresholds of the simulator to emulate those employed by the radio cards at each one of these nodes. We utilize a moderate fading Nakagami propagation model since the actual TFA network is located in a residential urban area, and we are only considering stationary clients.

In our evaluation, we study the performance of DOC by first exploring the number of cooperative packet transmissions at both the client level as well as the backhaul level in order to visualize to what extent the relay assists these nodes. This is basically a measure of how necessary the relay is for a given source-destination pair. We run a total of 10 simulations and average our results. Each simulation runs for 700 seconds, however, we eliminate the first and last 100 seconds in order to make sure the system is stable.

Figure 7.5 presents the percent of cooperative transmissions triggered due to adverse channel conditions at both clients, as well as backhaul nodes out of all source

transmission. We present results for some of the different types of flows encountered in the mesh network such as a 2-Hop, and 4-Hop routes where all nodes use omnidirectional antennas, as well as a 2-Hop route via a directional link.

For all clients, cooperation is triggered in at least 10% of the total transmissions. We also observed that at the client level, gains achieved from cooperation are similar to what we have presented for previous experiments. At the backhaul, the maximum percent of triggered cooperative packets occurs at the directional link. However this number is rather low, only reaching up to 2%. This happens mainly due to the following two reasons: First, APs transmit at a much higher power than clients. This means that at the backhaul, packets are more likely to arrive with a much higher SNR to either the gateway or a routing AP. Hence, instead of packet being lost due to channel quality, most are lost due to congestion and interference, which translates into having very little cooperative transmissions. On the other hand, clients, which are already transmitting at lower power, can also be affected by their distance to the closest AP they can associate with (i.e. recall these are randomly located to within 250 meters from a given AP).

Second, antenna gains between APs are also higher than those at the clients. Thus, a transmission from a client to an AP will not undergo the same gains as in the case where communication is solely among the backhaul nodes. Further, the discrepancy on the percent of cooperative packets between the directional link and the other two, comes from a higher packet loss at the directional interface which is mainly attributed to the extremely long distance between the two nodes connecting through this link.

In table 7.1 we present the per-flow average results for throughput achieved by the overall network. Observe that in average, cooperation achieves up to 14% throughput

gains. However, one flow was able to reach almost 70% gains whereas another one only experienced losses of around -10%. More importantly, notice the 75 percentile is located mostly between 0-10%. From this results we can conclude that only a few very specific flows see a substantial benefit from cooperation whereas most others do not experience any significant improvement. Even worse, some flows are affected by the additional interference originated from relays.

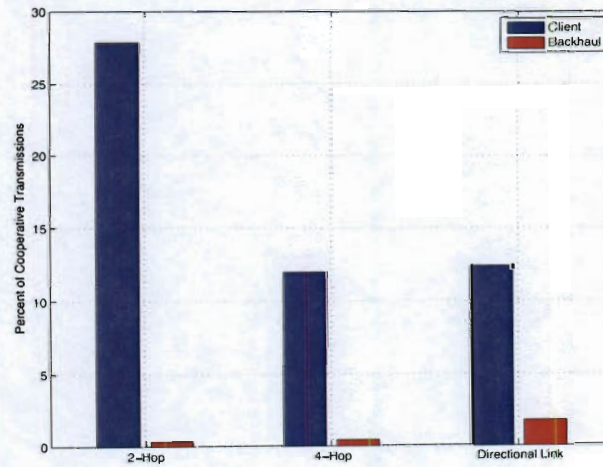


Figure 7.5 : Percent of cooperative transmissions *i)* out of the total originated packets by every client node and *ii)* out of the total forwarded packets by every backhaul node.

Findings: In large-scale networks, gains from cooperation we had observed for atomic scenarios are significantly diminished even for single-hop flows. This fact should give some insight on how cooperative protocols should base their decisions not only according to their local view of the network but also from a global perspective.

Avg. Per-Flow Throughput Gain	14.26%
Min Throughput Gain	-9.80%
Max Throughput Gain	69.44%
75 th Percentile	$-2.5\% \leq x \leq 11.0\%$
25 th Percentile	$11.0\% \leq x \leq 21.5\%$

Table 7.1 : Overall performance results of the TFA network

Chapter 8

Conclusion

In this work, we evaluate the performance of cooperative schemes in common networking scenarios that span everything from fully connected topologies, to cases leading to information asymmetry in both isolated and network-wide designs. We perform a study of the network factors that affect the gains that can be achieved through cooperative techniques under different small-scale networking scenarios consisting of at most two flows.

We identify these factors to be the lack of knowledge about the overall network state, distance between sources and destinations, as well as relay position and increased transmission footprint due to the activity of the relay. Further, we extend our evaluation to multi-flow, multi-hopping network configurations consisting of more complex interactions among nodes. In our work, we present results from both an experimental setup as well as simulations where we implement two different space diversity cooperative protocols. We demonstrate that the gains from cooperation achieved at small topologies become less significant in large-scale network scenarios.

Moreover, we show the wide variety of scenarios in which cooperation can be beneficial or detrimental to the overall performance of a wireless network. Finally, we believe these results can provide with the information necessary to help in the design of new algorithms and protocols that take advantage of cooperation and spatial diversity.

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